

Neutron stars initial spin period distribution

A.P. Igoshev^{1*} and S.B. Popov^{2†}

¹ *Sobolev Institute of Astronomy, Saint Petersburg State University, Universitetsky prospekt 28, 198504, Stariy Peterhof, Saint Petersburg, Russia*

² *Sternberg Astronomical Institute, Lomonosov Moscow State University, Universitetsky prospekt 13, 119991, Moscow, Russia*

ABSTRACT

We analyze different possibilities to explain the wide initial spin period distribution of radio pulsars presented by Noutsos et al. (2013). With a population synthesis modeling we demonstrate that magnetic field decay can be used to interpret the difference between the recent results by Noutsos et al. (2013) and those by Popov & Turolla (2012), where a much younger population of NSs associated with supernova remnants with known ages has been studied. In particular, an exponential field decay with $\tau_{\text{mag}} = 5$ Myrs can produce a “tail” in the reconstructed initial spin period distribution (as obtained by Noutsos et al. 2013) up to $P_0 > 1$ s starting with a standard gaussian with $\langle P_0 \rangle = 0.3$ s and $\sigma_P = 0.15$ s. Another option to explain the difference between initial spin period distributions from Noutsos et al. (2013) and Popov & Turolla (2012) — the emerging magnetic field — is also briefly discussed.

Key words: stars: neutron, pulsars: general

1 INTRODUCTION

Initial parameters of neutron stars (NSs) can be neither observed directly, nor calculated from the first principles, yet. Such parameters as initial magnetic field or initial spin period distributions, as well as initial velocity distribution, etc. are derived from observational data using different assumptions, sometimes via population synthesis modeling (Popov & Prokhorov 2007).

Recently, Noutsos et al. (2013) (hereafter N13) presented a detailed analysis of a sample of radio pulsars (PSRs) with relatively well-determined kinematic ages. Assuming standard magneto-dipole formula they reconstruct the initial spin period distributions for PSRs, and compare it with previous results. In particular, they provide comparison with the distribution proposed by Popov & Turolla (2012) (hereafter PT12) for the population of NSs associated with supernova remnants (SNRs) with known ages.

The sample of pulsars used by N13 has average ages of about a few million years. The NSs used by PT12 are much younger. The two initial spin period distributions do not coincide: the one by N13 is wider, even PSRs with initial spin periods $P_0 \gtrsim 1$ s are present. In PT12 the authors provide for many sources just upper limits on P_0 and they do not provide the initial spin period distribution. So it is difficult to compare directly the two distributions. However, as the data in PT12 are shown to be compatible with a gaussian distribution with $\langle P_0 \rangle = 0.1$ s and $\sigma_P = 0.1$ s, we compare data from N13 with two gaussians. The Kolmogorov-Smirnov test demonstrates that the probability that the data from N13 are compatible with the gaussian with $\langle P_0 \rangle = 0.1$ s and $\sigma_P = 0.1$ is $4.5 \cdot 10^{-9}$. Slightly wider

gaussians are also in correspondence with the data set in PT12, so we also compare the data from N13 with the gaussian $\langle P_0 \rangle = 0.2$ s and $\sigma_P = 0.2$ s. The probability that they come from the same distribution is 0.0582. We conclude that distributions from N13 and PT12 cannot correspond to the same population of sources.

In this note we discuss how two initial spin period distributions can be brought in correspondence with each other. We propose two possibilities: field decay or emerging magnetic field buried earlier by the fall-back accretion.

2 DECAYING MAGNETIC FIELD

In the paper by N13 initial periods are reconstructed from the present ones using the magneto-dipole formula with all parameters (magnetic field, angle between spin and magnetic axis) constant in time. In PT12 the authors used the same assumptions, but objects in their sample are about two orders of magnitude younger. For this young sample of objects in SNRs, evolution of the field or of the angle cannot be very significant, but it can influence the other one studied in N13.

Below we do not speak separately about the angle evolution. Instead, one can assume that the “magnetic field” in the magneto-dipole formula is actually an “effective field”, $B_{\text{eff}} = B \sin \chi$ where χ is the angle between spin and magnetic axes and B is the magnetic field at the NS equator.

The process of field decay in pulsars can explain the long initial spin periods, inferred under the assumption of a constant magnetic field, as earlier braking was faster than it is now. This would widen the reconstructed (under assumption of constant parameters) P_0 distribution. Let us give an example.

Rapid exponential field decay on the time scale of about few

* E-mail: ignotur@gmail.com

† E-mail: sergopolar@gmail.com

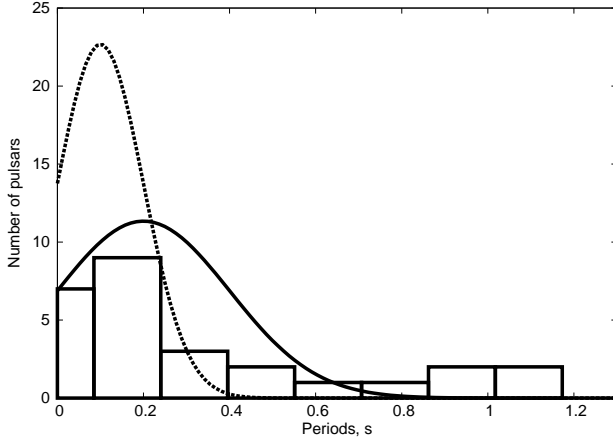


Figure 1. Initial spin period distributions. The histogram represents initial periods from N13. The solid line is a gaussian with $\langle P_0 \rangle = 0.2$ s and $\sigma_P = 0.2$ s. The dotted line is a $\langle P_0 \rangle = 0.1$ s and $\sigma_P = 0.1$ s. All gaussians are normalized to the same number of objects as in the histogram.

million years is assumed to be excluded for NSs with standard field values (magnetars are not discussed here) basing on the population synthesis of radio pulsars (Faucher-Giguère & Kaspi 2006). However, longer time scales, closer to 10^7 years are possible (Pons et al. 2009). In particular, we choose for an illustration a characteristic time scale for the exponential field decay equal to 5 Myrs, as it was proposed by Gonthier et al. (2002) (see, however, critics in Faucher-Giguère & Kaspi 2006). More complicated models of field decay can also be used. For example, as the NS crust cools down at ages > 1 Myr the Hall drift may become important (Pons et al. 2009); then the rate of decay depends on details of the NS parameters, but for illustration purposes we prefer to use a monotonic exponential decay which proceeds with the same rate for all NSs.

Note, also, that the distribution with $\langle P_0 \rangle = 0.1$ s and $\sigma_P = 0.1$ s, for which N13 make comparison, was given in PT12 just as an illustration, not as the best fit. Variants with larger $\langle P_0 \rangle$ and σ_P are also possible, as it was noted in that paper. We take the following initial distributions. Spin periods have gaussian distribution with $\sigma_P = 0.15$ and mean value 0.3 s. Initial magnetic field has gaussian distribution in log with $\sigma_B = 0.55$ and mean value $\log B_0/[G]=12.65$ (Faucher-Giguère & Kaspi 2006; Popov et al. 2010).

The magneto-rotational evolution of PSRs in the population synthesis model was calculated for exponentially decaying magnetic field:

$$B = B_0 \exp\left(-\frac{t}{\tau_{\text{mag}}}\right). \quad (1)$$

As we want to compare our calculations with results from N13 then we need to take relatively young (with respect to the whole population of normal PSRs) and not very faraway objects. To do so we consider only not-too-old pulsars at distances smaller than 5 kpc from the Sun. The latter condition is related to the potential difficulty in estimating the kinematic ages for distant PSRs. In the sample from N13 the majority of objects with estimated P_0 have distances $\lesssim 5$ kpc. In addition, among distant objects dim PSRs can be missed, which potentially may result in a bias in the P_0 distribution. To avoid this, we exclude distant NSs in our model limiting the distance to a value close to the maximum in the sample from N13. To select young objects we take PSRs with *true* ages below 10^7 year. On the other hand, since for very young NSs it is

difficult to estimate kinematic ages we neglect objects with $t_{\text{true}} < 10^5$ yrs (indeed, such NSs are absent in N13).

Let us briefly describe the population synthesis model we use. Pulsars are born with constant rate (the exact value is not important for our study) in four spiral arms which are parametrized by a logarithmic spiral (Vallée 2005). We follow evolution of each pulsar in the model for $5 \cdot 10^8$ yrs. The motion of the pulsar is numerically integrated in the gravitational potential of the Galaxy. The potential is chosen in the same form as in Faucher-Giguère & Kaspi (2006), i.e. $\phi_G(r, z) = \phi_{\text{dh}}(r, z) + \phi_b(r, z) + \phi_n(r, z)$. Here ϕ_{dh} is the potential of the disk and halo, $\phi_b(r, z)$ is the potential of the bulge, and $\phi_n(r, z)$ is the potential of the Galactic nucleus (for details see Kuijken & Gilmore 1989). The kick velocity is sampled from the double-sided exponential distribution:

$$p(v_l) = \frac{1}{2\langle v_l \rangle} \exp\left(-\frac{|v_l|}{\langle v_l \rangle}\right), \quad (2)$$

with $\langle v_l \rangle = 180 \text{ km s}^{-1}$ (Faucher-Giguère & Kaspi 2006), and $|v_l|$ is the absolute value of v_l . Every component of the kick velocity is randomly generated according to the probability function (Eq. 2). We neglect the Shklovskii effect as well as changes of the relative position of the Sun and spiral arms.

The dispersion measure is calculated according to the NE2001 electron density model (Cordes & Lazio 2002). The spin period of a pulsar at the moment of observation is calculated by integrating the standard magneto-dipole formula:

$$P^2(t) = P_0^2 + 2K \int_0^t B(t')^2 dt'. \quad (3)$$

Here $K = 8\pi^2 R^6 / (3Ic^3) = 10^{-39} \text{ cm s}^3 \text{ g}^{-1}$, R is a NS radius, I is the moment of inertia, and c is the speed of light. $B(t)$ is calculated according to Eq. (1).

A pulsar is considered to be detected if its luminosity exceeds S_{min} for the Parkes multibeam (Manchester et al. 2001) or Swinburne survey (Edwards et al. 2001), and if it is located within a 15° (full width) stripe along the Galactic plane. To calculate beaming and radio luminosity we use the same assumptions as in the best model in Faucher-Giguère & Kaspi (2006). A pulsar is assumed to be observable till it crosses the death-line (Ruderman & Sutherland 1975; Rawley et al. 1986):

$$\frac{B}{P^2} < 0.12 \cdot 10^{12} \text{ G s}^{-2}. \quad (4)$$

After we obtained a synthetic population of observed radio pulsars we reconstruct the initial spin period distribution assuming the magneto-dipole formula with constant parameters, i.e. we follow the procedure used by N13 :

$$P_0 = P \sqrt{1 - \frac{t_{\text{true}}}{\tau}}. \quad (5)$$

Here P is the present spin period, τ is the characteristic (spin-down) age, and t_{true} is the true age of a pulsar, as computed from the model, in contrast to the approach by N13 where the most probable estimate based on the kinematic age is used. However, this assumption cannot cause problems because typically for PSRs from N13 the kinematic age, t_{kin} , should be very close to the true age.

We use the classical definition of the characteristic age:

$$\tau = \frac{P}{2\dot{P}}. \quad (6)$$

It is expected that P_0 calculated with Eq. (5) is longer in the case of magnetic field decay. Indeed, we can write:

$$P^2(t) = P_0^2 + 2KB_0^2 \int_0^t f^2(t) dt, \quad (7)$$

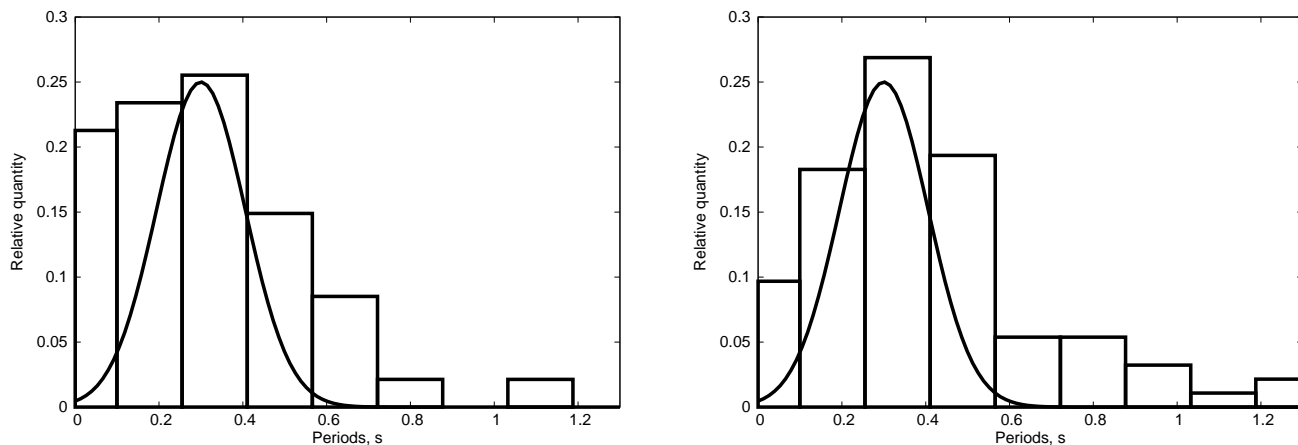


Figure 2. The histograms show the reconstructed distribution of P_0 for the population synthesis model. The population evolved with exponentially decaying magnetic field, $\tau_{\text{mag}} = 5$ Myrs. Only PSRs with $d < 5$ kpc (at the moment of observation) are taken into account. The solid line in both panels represents the true initial distribution of periods used in our calculations. In the left panel we show results where PSRs with characteristic ages $> 10^7$ yrs are neglected. In the right panel — objects with *true* ages $> 10^7$ yrs are not taken into account. In both plots objects with $t_{\text{true}} < 10^5$ yrs are not used.

where B_0 is the initial magnetic field, and $f(t)$ is the magnetic field decay function. Then:

$$\tau = \frac{\tau_{\text{corr}}}{f^2(t)} + \frac{\int_0^t f^2(t) dt}{f^2(t)}, \quad (8)$$

where $\tau_{\text{corr}} = P_0^2 / (2KB_0^2)$ is a correction term, and physically this is the “initial spin-down age”.

It is known that for normal pulsars ($B \sim 10^{12}$ G) with ages larger than $\sim 10^5$ years τ_{corr} is usually much smaller than τ and, therefore, changes in the reconstructed P_0 in Eq. (5) are determined mainly by the magnetic field decay. In fact, when decay starts to be important the second term in Eq. (8) is always larger than the first one, and they grow with approximately the same rate. If the field evolution, contained in $f(t)$, is the same for all PSRs, then when τ_{corr} starts to be insignificant, the characteristic ages of PSRs with the same t_{true} are approximately equal (Igoshev 2012). However, P is still determined by B_0 , see Eq. (7). So, the reconstructed initial periods appear to be dependent on B_0 .

Results of population synthesis simulations are shown in Fig. 2. As a histogram we present the reconstructed distribution of P_0 (to be compared with Fig. 17 in N13, see also Fig. 1). The real initial spin period distribution used in the model is shown with a solid line. We show also a variant of this plot where the condition $t_{\text{true}} < 10^7$ yrs was replaced by $\tau < 10^7$ yrs. The motivation is that in N13 all but one PSRs with estimated initial spin periods satisfy this condition. As it can be seen, there is virtually no difference between two panels.

Obviously, the reconstructed distribution looks much different from the real underlying initial distribution, but very similar to the one derived by N13. This demonstrates that magnetic field decay can potentially explain the difference between two distributions for realistic parameters. This is the main result of our paper. Of course, some fine tuning is possible, but we think that with the current low statistics this is premature.

3 DISCUSSION

3.1 Re-emerging magnetic field

Another possibility to explain the difference between distributions from N13 and PT12 is related to the idea of emerging magnetic field after it has been buried due to strong fall-back accretion (Muslimov & Page 1995; Ho 2011; Viganò & Pons 2012; Bernal et al. 2012)¹.

The initial spin period distribution derived by N13 for values below $\sim 0.3 - 0.4$ s is not much in contradiction with PT12. The main problem is due to objects with $P_0 \sim 1$ s, which are just a few. One way to explain them is to find a physical reason why they are hidden among young sources (analyzed by PT12) and visible among the older population (studied in N13). Fall-back which buries the magnetic field can do the job if the field emerges faster than a few hundred thousand years.

Among young NSs in supernova remnants there is a group of so-called central compact objects (CCOs) for which spin periods are not measured as no pulsations (in radio or/and in X-rays) are observed. They are assumed to be relatives of so-called anti-magnetars (Gotthelf et al. 2013) which have long P_0 : $\sim 0.1 - 0.5$ s. Then we can suspect that their initial spin periods are also long. One can speculate that they are on average longer than those of CCOs with observed pulsations. For example, it is possible to propose a hypothesis that for longer initial spin periods fall-back is more significant, and so the field is buried deeper, then we do not see pulsations, which are due to non-isotropic temperature distribution produced by the magnetic field. For example, Güneydaş & Ekşi (2013) provide arguments in favour of a correlation between kick and amount of matter accreted during a fall-back episode. On the other hand, Spruit & Phinney (1998) discuss a correlation between the value of kick velocity and initial spin². Additional kick, in their model, can spin-up the star, so the larger the kick, the faster the spin. Then NSs with smaller initial kicks can

¹ About fall-back see, for example, Colpi et al. 1996 and references to early studies therein.

² Note, however, that our analysis using P_0 data from N13, PT12, and velocities from the ATNF catalogue does not support any correlation between P_0 and velocity.

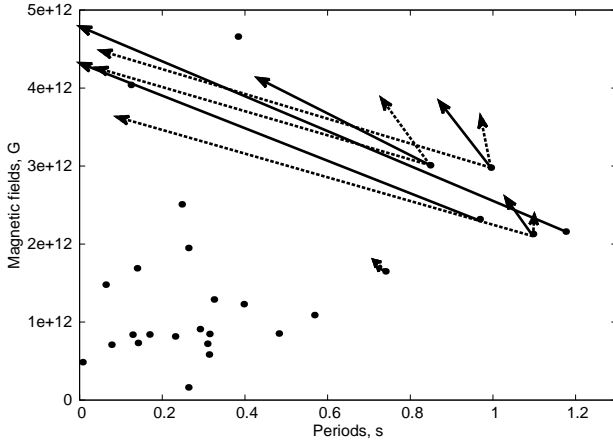


Figure 3. $P_0 - B$ plot for sources from N13. Initial spin periods are reconstructed from the present day values using the magneto-dipole formula, constant field, and kinematic age as the true age. Arrows point to initial parameters of pulsars with reconstructed $P_0 > 0.6$ s if the exponential magnetic field decay with τ_{mag} was operating. If for a PSR several arrows are plotted, then solid lines correspond to the most probable estimate of kinematic age, t_{kin} , from N13, and dashed lines, to the lower and upper limits on t_{kin} . If just one solid arrow is plotted, then it corresponds to the lower limit on t_{kin} , because large values do not allow to derive any estimate for the initial spin period.

have longer spin periods and larger amounts of accreted matter. If this is the case, then among young NSs (analyzed by PT12) sources with large initial spins should not be visible, but on the timescale $10^4 - 10^5$ years their fields can re-emerge (otherwise, they should be visible among high-mass X-ray binaries, but this is not the case, see Popov & Turolla 2013), and so they contribute to the sample analyzed by N13.

3.2 $P_0 - B$ correlation

Here we want to discuss a possible correlation between present magnetic field (determined as $B \sim \sqrt{P\dot{P}}$) and initial spin period reconstructed with Eq. (5). We use the data from Table 1 in N13. Results are shown in Fig. 3. It seems, mostly due to a group of sources with $P_0 \gtrsim 0.6$ s, that for longer initial spin periods the magnetic field is higher. The plot $P_0 - B$ presented by PT12 is much different. So, again we have to explain the differences. The question is: is it a real correlation, or this is an artefact due the assumptions made to derive P_0 , or is it just a fluctuation?

Statistics is rather poor, and two different conclusions can be made. Either the correlation appears only due to the group of six PSRs with the longest P_0 , or the correlation is valid for the whole range of P_0 (the two outlying PSRs with the largest fields can be due to a fluctuation). Also, of course, it is probable that this feature of the distribution is just due to some unknown selection effects, but we do not discuss this possibility further.

We calculate similar plots with a population synthesis model. Results are shown in Fig. 4. In the left panel we show the case for the constant magnetic field, and in the right that of a decaying field with $\tau_{\text{mag}} = 5 \cdot 10^6$ yrs. Initial spin periods are reconstructed using Eq. (5). We select objects with true ages in the interval $10^5 < t_{\text{true}} < 10^7$ years. Both plots are not similar to Fig. 3: no obvious correlation is visible in any panel. The main difference between the two distributions is that for decayed fields we have objects with long reconstructed P_0 , as expected, and the top-left

region in the right panel is underpopulated as sources are shifted toward the bottom-right part of the plot. However, if we remove objects with $\tau > 10^7$ yrs (which are absent in the sample from N13), then the plot for the decayed field starts to look relatively similar to Fig. 3. If in the original data from N13 the correlation is valid for the whole range, then this can be considered as an argument in favour of the decaying field model. We additionally illustrate it adding to Fig. 3 arrows connecting reconstructed in N13 initial parameters with those obtained in the model with decaying magnetic field. Clearly, PSRs are moved to much shorter initial periods, and so no contradiction with the distribution proposed in PT12 exists.

In the opposite case, if the correlation in Fig. 3 is just due to six objects on the right, then we have a separate population of sources with long initial spin periods, and this, in our opinion, can be an argument in favour of emerging magnetic field. In PT12 the authors did not find any correlation between P_0 and B , but in their sample of young objects, most probably, there are no (or very few) PSRs with re-emerged fields, and magnetic fields could not change significantly due to decay. Note also, that CCOs can have large toroidal fields (Shabaltas & Lai 2012), and dipole fields can be at least correlated with toroidal, then objects with long initial spin periods can have larger magnetic fields (after they fully emerge), as we see in Fig. 3.

To distinguish between the two possibilities more sources with known ages are necessary.

3.3 Phenomenological magnetic field decay model

More complicated magnetic field decay models exist, and they also can be applied to reproduce the $P_0 - B$ plot with the data from N13. As an illustration we use a model developed by Igoshev, in preparation (see also Igoshev 2012) for a different study, but applicable also in this case. Parameters and evolutionary laws in the model were fitted using the data on τ distributions for a large sample of known PSRs.

As there are no pulsars with $\tau > 10^7$ years in the sample from N13 it may indicate that (despite the field decay) for ages $t_{\text{true}} \sim 10^6 - 10^7$ yrs we have $t_{\text{true}} \sim \tau$. The phenomenological model of decay suggested by Igoshev (2012) satisfies this condition. The model is parametrised by the following equation:

$$f_{\text{corr}}(t) = \left(\left(a \frac{t}{t_0} \right)^\gamma + C \right)^{-1}. \quad (9)$$

Parameters of the fine-tuned model have the following values: $t_0 = 10000$ yrs, $a = 0.034$, $\gamma = 1.17$, $C = 0.84$. Initial distributions are the following: $\langle P_0 \rangle = 0.2$ s, $\sigma_P = 0.15$ s, and $\langle \log B_0/[G] \rangle = 12.92$, $\sigma_B = 0.47$. For $t_{\text{true}} > 3.5 \cdot 10^5$ yrs magnetic fields are assumed to be constant.

The distribution of pulsars in $P_0 - B$ plane calculated within this model is similar to the one from N13, see Fig. 5. Despite the fact that this distribution is based on a multi-parametric, phenomenological model, this exercise illustrates that the field decay can be fine-tuned to produce the $P_0 - B$ similar to the results by N13.

4 CONCLUSIONS

In this work we studied if results on the initial spin period distributions obtained in PT12 and N13 can be brought in correspondence with each other. In both papers the authors reconstructed initial periods using independent estimates of NSs ages (SNR age in PT12,

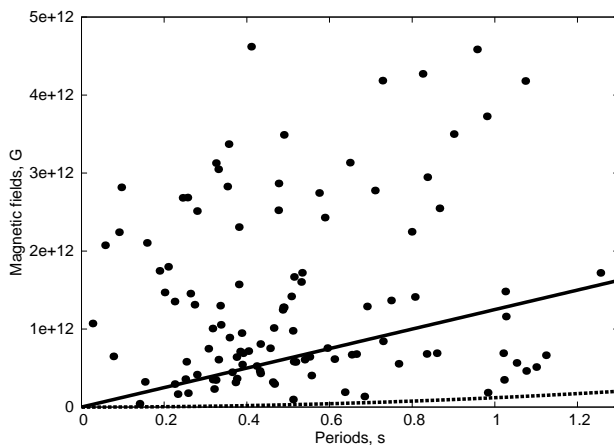
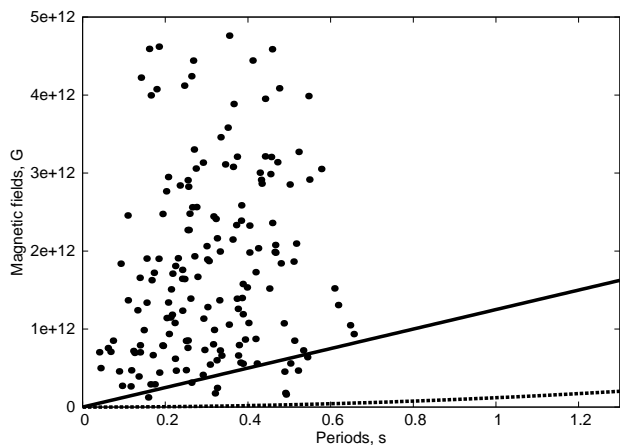


Figure 4. $P_0 - B$ plots for synthetic populations. Initial spin periods are reconstructed according to Eq. (5). Fields represent present day values. Only objects with $10^5 < t_{\text{true}} < 10^7$ yrs are plotted. Left: constant magnetic field. Right: decaying field with $\tau_{\text{mag}} = 5$ Myrs. The solid line in each plot corresponds to $\tau = 10^7$ yrs, the dashed line in the bottom, to the death line.

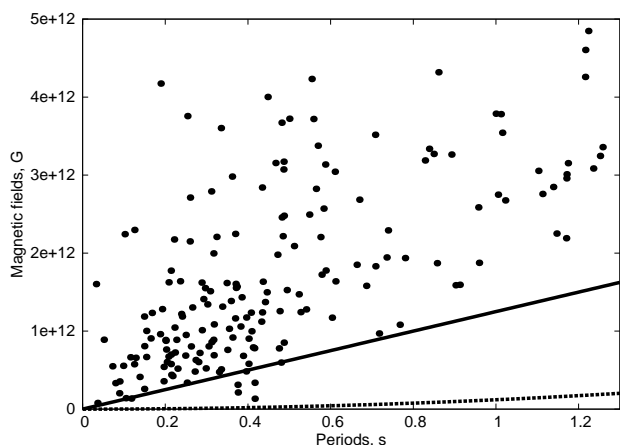


Figure 5. $P_0 - B$ plot for the phenomenological magnetic field evolution model. Initial spin periods are reconstructed according to Eq. (5). Present day values of the magnetic field are shown. Only objects with $10^5 < t_{\text{true}} < 10^7$ yrs are plotted. Magnetic field evolution is calculated according to Eq. (9). The solid line corresponds to $\tau = 10^7$ yrs. The dashed line in the bottom corresponds to the death line.

and kinematic age in N13) and the standard magneto-dipole formula with braking index $n = 3$. One sample (PT12) contains objects with ages from a few thousand years up to ~ 100 kyrs. The other sample (N13) contains much older NSs with an average age of about a few million years. We analyzed if magnetic field evolution can produce both reconstructed initial period distributions starting with the same true distribution.

We apply the population synthesis technique to scrutinize the effects of magnetic field decay on the reconstructed P_0 distribution. We found that a simple exponential decay with $\tau_{\text{mag}} = 5$ Myrs can reproduce a narrow distribution for younger objects, and much wider one for objects with ages \sim few Myrs, in correspondence with PT12 and N13. Potentially, magnetic field evolution can be fine-tuned to reproduced additional features of the sample presented in N13, but such calculations are beyond the aims of this note.

In addition, we briefly discussed the possibility that re-emerging magnetic field can be also used to explain the differences

between the two initial spin period distributions, as NSs with longer initial spin periods can be hidden among the younger population studied in PT12. However, we do not model this mechanism.

We conclude noticing that the differences between initial spin period distributions obtained by PT12 and N13 are due to evolution of the magnetic field on the time scale smaller than a few million years. To distinguish between different models of field evolution it is necessary to increase statistics of NSs with known ages.

ACKNOWLEDGMENTS

We thank Roberto Turolla for discussions and numerous comments. We are in debt to the unknown referee, who made many useful remarks and suggestions which helped a lot to improve the paper. The work of S.P. was supported by the RFBR grant 12-02-00186. The work of A.P. was supported by Saint Petersburg University grant 6.38.73.2011.

REFERENCES

- Bernal C. G., Page D., Lee W. H., 2012, ArXiv e-prints, arXiv: 1212.0464
- Colpi M., Shapiro S. L., Wasserman I., 1996, ApJ, 470, 1075
- Cordes J. M., Lazio T. J. W., 2002, ArXiv Astrophysics e-prints, astro-ph/0207156
- Edwards R. T., Bailes M., van Straten W., Britton M. C., 2001, MNRAS, 326, 358
- Faucher-Giguère C.-A., Kaspi V. M., 2006, ApJ, 643, 332
- Gonthier P. L., Ouellette M. S., Berrier J., O'Brien S., Harding A. K., 2002, ApJ, 565, 482
- Gotthelf E. V., Halpern J. P., Alford J., 2013, ApJ, 765, 58
- Güneydaş A., Ekşi K. Y., 2013, MNRAS, 430, L59
- Ho W. C. G., 2011, MNRAS, 414, 2567
- Igoshev A. P., 2012, ArXiv e-prints, arXiv: 1204.3445
- Kuijken K., Gilmore G., 1989, MNRAS, 239, 651
- Manchester R. N., Lyne A. G., Camilo F., Bell J. F., Kaspi V. M., D'Amico N., McKay N. P. F., Crawford F., Stairs I. H., Possenti A., Kramer M., Sheppard D. C., 2001, MNRAS, 328, 17
- Muslimov A., Page D., 1995, ApJ, 440, L77

- Noutsos A., Schnitzeler D. H. F. M., Keane E. F., Kramer M., Johnston S., 2013, MNRAS, p. 718
- Pons J. A., Miralles J. A., Geppert U., 2009, A&A, 496, 207
- Popov S. B., Pons J. A., Miralles J. A., Boldin P. A., Posselt B., 2010, MNRAS, 401, 2675
- Popov S. B., Prokhorov M. E., 2007, Physics Uspekhi, 50, 1123
- Popov S. B., Turolla R., 2012, Ap&SS, 341, 457
- Popov S. B., Turolla R., 2013, in Lewandowski W., Maron O., Kijak J., eds, Astronomical Society of the Pacific Conference Series Vol. 466 of Astronomical Society of the Pacific Conference Series, Initial Parameters of Neutron Stars. p. 191
- Rawley L. A., Taylor J. H., Davis M. M., 1986, Nature, 319, 383
- Ruderman M. A., Sutherland P. G., 1975, ApJ, 196, 51
- Shabaltas N., Lai D., 2012, ApJ, 748, 148
- Spruit H., Phinney E. S., 1998, Nature, 393, 139
- Vallée J. P., 2005, AJ, 130, 569
- Viganò D., Pons J. A., 2012, MNRAS, 425, 2487